

University of Technology Sydney

**Assisting Product Designers with Balancing Strength
and Surface Texture of Handheld Products Made from
3D Printed Polymers**

**by
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Doctor of Philosophy

in the
School of Design
Faculty of Design Architecture and Building

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Certificate of original authorship

I, Stefan Lie, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Design, Faculty of Design Architecture and Building at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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The world of organized artifice is transforming in ways that are poorly understood and little explored. There are two reasons why this is happening. First, new forms of design and manufacture are appearing that lack historical precedent, and are bound to create substantial novelty. Second, the production methods currently used are not sustainable. They are large in scale, have long histories, and have been extensively researched and developed, but they can't go on in their present form. The status quo uses archaic forms of energy and materials which are finite and toxic. They wreck the climate, poison the populace and foment resource wars. They have no future.

— Bruce Sterling in *Shaping Things* (2005, p. 5)

Contents

Certificate of original Authorship	2
Acknowledgments	3
Preface	4
List of figures	8
List of tables	12
Glossary of terms and abbreviations	14
Abstract	16
Chapter 1. Introduction	17
1.1 Background and motivation	20
Chapter 2. Existing knowledge and related literature	25
2.1 3D printing	25
2.1.1 Types of 3D printing processes and available materials	27
2.1.2 Post-processing of 3D printed polymer parts	28
2.1.3 Discussion of 3D printing	33
2.2 The process of designing a product	35
2.2.1 Design for manufacturing (DFM)	37
2.2.2 Designing for 3D printing/additive manufacturing (DFAM)	38
2.2.3 Discussion of product design process	43
2.3 End-use products made from 3D printed polymers	44
2.3.1 Static mechanical properties of three 3D printed polymers	55
2.3.2 Benchmark studies of 3D printed polymers	60
2.3.3 AM polymer/process specific studies	61
Studies of Fused Deposition Modelling in ABS	61
Studies of Material Jetting in TPGDA	69
Studies of Selective Laser Sintering in PA	75
2.3.4 Discussion of end-use products made through 3D printing	80
2.4 Strategies to optimise part orientation	81
2.4.1 Discussion of methods to optimise part orientation	85
2.5 Interacting with products	86
2.5.1 Discussion of interacting with products	93
2.6 Discussion of existing knowledge and related literature	94
Chapter 3.0 Research questions and methodology	96
3.1 Research questions	98
3.2 Methodology	98
3.2.1 Methodology part 1	101

3.2.2 Methodology part 2	104
3.3 Limitations of scope	106
3.4 Research hypothesis	108
Chapter 4.0 Experiments	112
4.1 Experiments to determine the mechanical properties of the three 3D printed polymers at a 45 deg incline	112
4.1.1 Making the test specimens	114
4.1.2 Tensile testing	117
4.1.3 Izod impact testing (notched)	121
4.1.4 Flexural or 3-point bend testing	124
4.2 Experiment to determine clear visual representation of the surface of a 3D printed part prior to building	126
Chapter 5.0 Results	138
5.1 Mechanical property test results of the three 3D printed polymers	138
5.1.1 Results for tensile testing	139
5.1.2 Results for Izod impact testing	142
5.1.3 Results for 3 point bend testing	143
5.2 Results for a clear visual surface representation	144
Chapter 6.0 Analysis and communication of results	147
6.1 Analysis of the results in response to research question 1a	147
6.1.1 Variation of ABS properties based on build orientation	148
6.1.2 Variation of TPGDA properties based on build orientation	150
6.1.3 Variation of PA properties based on build orientation	151
6.2 Analysis of the results in response to research question 1b	152
6.3 Analysis of the results in response to research question 2	154
Chapter 7.0 Discussion	155
7.1 Selecting a surface appearance	156
Application to practice through design process	160
7.2 Selecting the most suitable polymer based on a mechanical property	161
7.2.1 Example of selecting a polymer based on max. tensile strength	161
Application to practice through design process	163
7.2.2 Example of selecting a polymer based on impact strength	164
Application to practice through design process	165
7.2.3 Example of selecting a polymer based on flexural strength	165
Application to practice through design process	167

7.3 Selecting the most suitable build orientation for each polymer	167
7.3.1 Scenario 1: Selecting a build orientation for ABS	168
7.3.2 Selecting a build orientation for TPGDA and PA	173
Application to practice through design process	174
7.4 Balancing mechanical properties with surface appearance	175
7.4.1 Scenario 2: Visualisation of a polymer based on max tensile strength	175
Application to practice through design process	184
7.4.2 Scenario 3: Redesign of a product to suit a specific polymer	185
Application to practice through design process	200
7.5 The approach and tools in review	200
Chapter 8.0 Conclusion	202
8.1 Thesis recap	202
8.2 Contribution to knowledge	207
8.2.1 A new approach for product design	207
8.2.2 Material property data	210
8.2.3 Unanticipated discoveries	211
8.3 Wider reaching implications	212
Appendices	216
Appendix A	216
ProJet general post processing wax removal process	
Appendix B	217
Supplier material data sheets for ABS, TPGDA and PA	
Appendix C	220
Load cell certification by Australian Calibration Services	
Appendix D	221
Sample spreadsheet of recorded tensile specimen dimensions	
Appendix E	222
Izod impact testing report by LMATS Pty Ltd	
Appendix F	234
Sample spreadsheet 3-point bend specimen dimensions	
Appendix G	235
Human ethics application with Nil/Neg risk to participants	
Appendix H	236
ASTM standard: D638-14, D256 – 10 and D790 – 15	
Bibliography	285

List of figures

Figure 2.1:	General post-processing of an SLS part (courtesy of i.materialise).	29
Figure 2.2:	Teapot 3D printed in ABS by FDM with support material still in place.	29
Figure 2.3:	Stair-stepping effect of FDM in ABS, layer height 0.254mm.	30
Figure 2.4:	Stair-stepping and surface roughness of SLS in PA, layer height 0.1mm.	31
Figure 2.5:	3D printed surface textures (courtesy of Lehrmitt Design Studios).	32
Figure 2.6:	Schematic representation of the FDM process (courtesy of additively).	33
Figure 2.7:	Schematic representation of the MJ process (courtesy of additively).	34
Figure 2.8:	Schematic representation of the SLS process (courtesy of additively).	34
Figure 2.9:	Immortal-Mechanical-Paddles by Soludus on a PS4 controller.	40
Figure 2.10:	E-NABLE prosthetic limb (courtesy of E-NABLE Medellin).	45
Figure 2.11:	3D printed Limelight track lights (courtesy of Limelight).	46
Figure 2.12:	3D printed lug-nut starter tool (courtesy of Eckhart).	46
Figure 2.13:	Typical setup of the Sydney Harbour Bridge grit-blasting robot.	48
Figure 2.14:	A robot set up ready to blast a section of the Sydney Harbour Bridge.	48
Figure 2.15:	The interactive stepping tiles in use.	49
Figure 2.16:	The main tile.	50
Figure 2.17:	Warped main tile.	51
Figure 2.18:	Complete Visionsearch system set up and in use.	52
Figure 2.19:	How a Head Distancer is used.	53
Figure 2.20:	Visionsearch Head Distancer fully assembled.	53
Figure 2.21:	Orthogonal orientation notation (ASTM 2013b).	57
Figure 2.22:	Inclined build orientations do not have an ASTM notation.	57
Figure 2.23:	Schematic of FDM extrusion head (courtesy of MegaDepot).	62
Figure 2.24:	Detail of ABS tensile specimen built in the XYZ (HF) orientation.	62
Figure 2.25:	SEM cross section of ABS built in HF orientation.	64
Figure 2.26:	SEM cross section of ABS built in HoE orientation.	64
Figure 2.27:	HF orientation (perspective view).	65
Figure 2.28:	HoE (top view).	65
Figure 2.29:	Raster pattern experiments by Ziemian, Sharma and Ziemian.	66
Figure 2.30:	Schematic image of MJ process (Barclift & Williams 2012, p. 876).	70
Figure 2.31:	Orthogonal orientation notation according to ASTM (ASTM 2013b).	74
Figure 2.32:	Schematic of SLS process (courtesy of additively).	75

Figure 2.33:	Flow chart of Leuteneker-Twelsiek, Klahn, and Meboldt's method.	84
Figure 2.34:	Salt and Pepper Maracas by Naoto Fukasawa.	87
Figure 2.35:	3D printed nautilus shell jewellery piece showing build steps.	89
Figure 2.36:	3D printed jewellery pieces showing build steps.	90
Figure 2.37:	Toolpath visualisation through Stratasys Catalyst software.	91
Figure 2.38:	Effect of orientation upon surface roughness visualisation.	92
Figure 2.39:	Best surface quality on a selected area of a model.	93
Figure 3.1:	Diagram of the methodology.	100
Figure 3.2:	Orthogonal orientation notation (ASTM 2013b).	102
Figure 3.3:	Inclined build orientations do not have an ASTM notation.	103
Figure 3.4:	Diagram of Methodology Part 1.	104
Figure 3.5:	Diagram of Methodology Part 2.	105
Figure 3.6:	Diagram of the methodology.	110
Figure 4.1:	Tensile specimen build orientation and arrangement for ABS and TPGDA.	114
Figure 4.2:	Tensile specimen build orientation and arrangement for PA.	115
Figure 4.3:	Izod impact specimen build orientation for ABS, TPGDA and PA.	115
Figure 4.4:	Flexural specimen build orientation for ABS, TPGDA and PA.	116
Figure 4.5:	Dimensions of tensile test specimens (all dimensions in mm).	118
Figure 4.6:	Tensile specimen build orientations for ABS and TPGDA.	119
Figure 4.7:	Tensile specimen build orientations for SLS in PA.	119
Figure 4.8:	Tensile test set up on Shimadzu ASG-X.	120
Figure 4.9:	Dimensions of Izod test specimens (all dimensions in mm).	122
Figure 4.10:	Izod specimen build orientations for ABS, TPGDA and PA.	122
Figure 4.11:	Izod test set up at LMATS Pty Ltd.	123
Figure 4.12:	Dimensions of flexural test specimens (all dimensions in mm).	124
Figure 4.13:	Flexural test specimens for ABS, TPGDA and PA.	125
Figure 4.14:	Flexural test setup on Shimadzu ASG-X.	120
Figure 4.15:	Image of the real turning handle.	130
Figure 4.16:	Software: Slicer (for Fusion 360 V1.0.0 by Autodesk).	131
Figure 4.17:	Software: Slic3r V1.2.9.	131
Figure 4.18:	Software: Simplify3D V4.0.1.	132
Figure 4.19:	Software: CatalystEx V3.5 (by Stratasys).	132
Figure 4.20:	Software: Cura V3.0.4 (for Ultimaker).	133
Figure 4.21:	Software: Cubicreator3 V3.6 (by Cubicon).	133

Figure 4.22:	Survey Welcome page.	135
Figure 4.23:	Main survey page.	136
Figure 4.24:	Survey thank you page.	137
Figure 5.1:	Raw data of test on SLS in V as output by Trapezium X.	139
Figure 5.2:	Calculated data for SLS in V as presented in Excel.	139
Figure 5.3:	Results of survey in terms of preference and percentage.	145
Figure 5.4:	Number of participants who completed and submitted the survey.	145
Figure 5.5:	Sample of individual response Progress (time spent on survey).	146
Figure 6.1:	ABS build orientation chart.	148
Figure 6.2:	TPGDA build orientation chart.	150
Figure 6.3:	PA build orientation chart.	151
Figure 6.4:	Comparison of tensile strength between the three polymers.	153
Figure 6.5:	Comparison of impact strength between the three polymers.	153
Figure 6.6:	Comparison of flexural strength between the three polymers.	154
Figure 7.1:	3D printed Nautilus shell pendant showing spiralling build steps.	157
Figure 7.2:	Nautilus shell pendant in Cura as it was built.	158
Figure 7.3:	Nautilus shell pendant in Cura in a different orientation.	159
Figure 7.4:	Gold and silver broaches showing build steps (courtesy of sculpteo).	160
Figure 7.5:	Comparison of tensile strength between the three polymers.	163
Figure 7.6:	Comparison of impact strength between the three polymers.	165
Figure 7.7:	Flexing clip on the battery cover of a remote (courtesy of Epson).	166
Figure 7.8:	Comparison of flexural strength between the three polymers.	167
Figure 7.9:	ABS Build Orientation Chart.	168
Figure 7.10:	ABS Impact Chart and views of acceptable range.	170
Figure 7.11:	Aviator Frame shown in HF orientation.	170
Figure 7.12:	Aviator Frame shown in I 45 orientation.	171
Figure 7.13:	Aviator frame shown in V orientation.	171
Figure 7.14:	HF to I 45 acceptable range of orientation shown in blue.	172
Figure 7.15:	Four build orientations in relation to mechanical properties of TPGDA.	174
Figure 7.16:	Four build orientations in relation to mechanical properties of PA.	174
Figure 7.17:	Diagram of Scenario 2.	176
Figure 7.18:	Comparison of tensile strength between the three polymers.	177
Figure 7.19:	PA build orientation chart.	178
Figure 7.20:	The acceptable range, shown in blue, for max tensile in PA.	179

Figure 7.21:	HF facing up and down.	180
Figure 7.22:	I 45 facing up and down.	180
Figure 7.23:	V option 1.	180
Figure 7.24:	V option 2.	180
Figure 7.25:	Horizontal build steps.	181
Figure 7.26:	Vertical build steps.	181
Figure 7.27:	I 45 options 1 and 2, both of which are asymmetrical.	182
Figure 7.28:	Frame with diagonal build steps.	182
Figure 7.29:	I 45 orientation.	183
Figure 7.30:	View of the section of the frame that will come in contact with the skin.	183
Figure 7.31:	Screen grab for print bureau operator.	184
Figure 7.32:	The Visionsearch Head Distancer.	185
Figure 7.33:	The Visionsearch Head Distancer in use.	186
Figure 7.34:	Outlined in red is the section of Head Distancer to be under tension.	187
Figure 7.35:	Outline shows where it was hollowed out to reduce material volume.	188
Figure 7.36:	Diagram of Scenario 3.	189
Figure 7.37:	Comparison charts of the three polymers.	190
Figure 7.38:	TPGDA build orientation chart.	191
Figure 7.39:	The three areas on the original design that will need to be redesigned.	192
Figure 7.40:	The redesigned Head Distancer.	193
Figure 7.41:	The changes to the three areas after redesigning the Head Distancer.	194
Figure 7.42:	Possible HF orientations.	196
Figure 7.43:	On its side could also be considered HF.	196
Figure 7.44:	The area of focus for selection of build orientation.	197
Figure 7.45:	Acceptable range for scenario 3.	197
Figure 7.46:	Final build orientation.	198
Figure 7.47:	Close-up showing surface detail.	199
Figure 7.48:	Screen grab for 3D print bureau operator.	199
Figure 8.1:	Methodology Diagram.	205

List of tables

Table 2.1:	Material data supplied by Stratasys for FDM in ABS	58
Table 2.2:	Material data supplied by 3D Systems for MJ in TPGDA	58
Table 2.3:	Material data supplied by EOS for SLS in PA	58
Table 2.4:	Build parameters used by Ahn et al (2002)	63
Table 2.5:	Chung Wang, Lin and Hu (2007), test results	63
Table 2.6:	Build parameters used by Chung Wang, Lin and Hu (2007)	66
Table 2.7:	Build parameters used by Ziemian, Sharma and Ziemian (2012)	67
Table 2.8:	Build parameters used by Rayegani and Onwubolu (2014)	68
Table 2.9:	Build parameters used by Pilipovic, Raos and Šercer (2009)	71
Table 2.10:	Build parameters used by Kęsy and Kotliński (2010)	71
Table 2.11:	Build parameters used by Barclift and Williams (2012)	72
Table 2.12:	Build parameters used by Cazon, Morer and Matey (2014)	73
Table 2.13:	Build parameters used by Mueller, Shea and Daraio (2015)	75
Table 2.14:	Build parameters used by Gibson and Shi (1997)	76
Table 2.15:	Build parameters used by Ajouk et al. (2006)	77
Table 2.16:	Build parameters used by Caulfield, McHugh and Lohfeld (2007)	78
Table 2.17:	Build parameters used by Starr, Gornet and Usher (2011)	78
Table 5.1:	ABS results for max. load, extension at max. load and max. strength	140
Table 5.2:	ABS results for load at fracture, extension at fracture, fracture strength	140
Table 5.3:	ABS results for Young's modulus	40
Table 5.4:	TPGDA results for max. load, extension at max. load and max. strength	141
Table 5.5:	TPGDA results for load at fracture, extension at fracture, fracture strength	141
Table 5.6:	TPGDA results for Young's modulus	141
Table 5.7:	PA results for max. load, extension at max. load and max. strength	141
Table 5.8:	PA results for Load at fracture, extension at fracture, fracture strength	142
Table 5.9:	PA results for Young's modulus	142
Table 5.10:	ABS results for Izod impact (notched) testing	142
Table 5.11:	TPGDA results for Izod impact (notched) testing	143
Table 5.12:	PA results for Izod impact (notched) testing	143
Table 5.13:	ABS results for max. load, stroke at max. load and flexural stress	143

Table 5.14:	TPGDA results for max. load, stroke at max. load and flexural stress	144
Table 5.15:	PA results for max. load, stroke at max. load and flexural stress	144
Table 5.16:	Breakdown of the results from the online survey	144
Table 6.1:	ABS build orientation variations of max. tensile strength	149
Table 6.2:	ABS build orientation variations of impact strength	149
Table 6.3:	ABS build orientation variations of max. flexural strength	149
Table 6.4:	TPGDA, build orientation variations of max. tensile strength	150
Table 6.5:	TPGDA build orientation variations of impact strength	151
Table 6.6:	TPGDA build orientation variations of max. flexural strength	151
Table 6.7:	PA build orientation variations of max. tensile strength	151
Table 6.8:	PA build orientation variations of impact strength	152
Table 6.9:	PA build orientation variations of max. flexural strength	152
Table 7.1:	ABS build orientation variations of impact strength	173
Table 7.2:	PA build orientation variations of max. tensile strength	178
Table 7.3:	TPGDA build orientation variations of max. tensile strength	195
Table 7.4:	TPGDA, build orientation variations of max. flexural strength	195

Glossary of terms and abbreviations

3D	Three dimensional.
3D printing	3 Dimensional printing.
ABS	Acrylonitrile Butadiene Styrene, a synthetic thermoplastic polymer used for AM in FDM machines.
Algorithm	A process or set of rules for followed in calculations or other problem-solving operations.
AM	Additive Manufacturing.
Anisotropic	Materials that have different physical properties when measured in different directions.
ASTM	American Society for Testing and Materials
Build orientation	The build orientation is the way parts are placed within the build volume.
Build volume	The specific x, y and z size of the 3D volume an AM machine is capable of building within, where x is width, y is depth and z is height, typically represented in mm. Parts to be built must fit within the build volume.
CAD	Computer Aided Design.
CNC	Computer Numerically Controlled.
DDM	Direct Digital Manufacturing.
DFM	Design For Manufacturing.
DFAM	Design For Additive Manufacturing.
DIN	Is German for Deutsches Institut für Normung (english: German Institute for Standardisation).
DIN EN ISO	The prefix to a test method, e.g. DIN EN ISO 180, that adheres to all three standards.
EN	Is German for Europa Norm (English: European Standard). Member states are required to adhere to EN standards.
End-use product	A product that has been manufactured for actual use, so must be usable, repeatedly if necessary, in the way that it is intended.
FDM	Fused Deposition Modelling.
Generic algorithm	A method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution. The algorithm repeatedly modifies a population of individual solutions (mathworks.com).
Handheld product	A portable product that can be used while it is being held and carried by one or both hands, ranging from static products such as bottle openers to hair dryers and complex electronic devices such as digital cameras.
HCI	Human Computer Interaction.

HF	Horizontal Flat. In the context of this research HF stands for a test specimen or part built in the XYZ orientation.
HoE	Horizontal on Edge. In the context of this research HoE stands for a test specimen or part built in the XZY orientation.
HRI	Human Robot Interaction.
I 45	Inclined at 45 degrees. In the context of this research I 45 stands for a test specimen or part built in the XZY at a 45 degree incline along X orientation.
ID	Industrial Design.
ISO	International Standards Organisation.
Isotropic	Materials that have the same physical properties when measured in different directions.
MJ	Material Jetting.
PA	Polyamide, a synthetic thermoplastic polymer used for AM in SLS machines.
Photopolymer	A light activated synthetic thermoset polymer that hardens when exposed to ultraviolet light, used for AM in MJ machines.
Polymer	Commonly referred to as plastic or resin, is a substance which has a molecular structure built up chiefly or completely from a large number of similar units bonded together.
SEM	Scanning Electron Microscope.
SLS	Selective Laser Sintering.
STL file	Standard Triangulation Language, the most widely accepted file format for 3D printing.
Thermoplast	A polymer that is formed by heating it up and hardens while cooling down, can be repeatedly remoulded through reheating.
Thermoset	A polymer that hardens during setting, by means of a chemical reaction that requires heat, cannot be remoulded through reheating or any other means.
TPGDA	Tripropylene Glycol Diacrylate, a synthetic thermoset photopolymer resin used for AM in MJ machines.
UTS	Ultimate Tensile Strength.
V	Vertical. In the context of this research V stands for a test specimen or part built in the ZXY orientation.
Visualisation	The representation of an object, situation, or set of information as a chart or other image.

Abstract

This research provides product designers using 3D printing to manufacture handheld products for end-use with a new approach, which enables them to make knowledge-directed decisions with regard to build orientation in relation to part strength and surface appearance. Because 3D printing machines deposit material in horizontal layers, they become anisotropic, which means they display different physical properties in different directions. To ascertain how much these physical properties differ, test samples were 3D printed in three different polymers and in three different build orientations, which were horizontal at 0 deg, inclined at 45 deg, and vertical at 90 deg.

Product designers also consider how the product will feel and look when it is interacted with, which makes the surface texture a key consideration. The surface of parts made through 3D printing can display characteristics such as stair-stepping; therefore, it is essential to visualise the surface before printing. To address this, six 3D printing software applications were assessed for their ability to visually represent the surface texture of a part before printing. The data resulting from the mechanical property testing was translated into a set of tools that represent the data graphically. The tools enable comparisons to be made between the mechanical properties of the three polymers, namely ABS (Acrylonitrile Butadiene Styrene), TPGDA (Tripropylene Glycol Diacrylate) and PA (Polyamide). The assessment of the six 3D printing software applications showed that Cura provides the most adequate representation of a part's surface.

This research is significant, since to date, no data or tools such as the results presented here on the mechanical properties of the three polymers at a 45 deg incline have been published, nor is there any data that enables the direct comparison of the three polymers in relation to horizontal, inclined at 45 degrees, and vertical build orientations. The ability to visually represent surface texture in relation to build orientation through Cura before printing will assist product designers. Both in combination or individually, the results of this research will provide product designers with a new approach which will help them make knowledge-directed decisions when designing a part to be manufactured through 3D printing in the polymers ABS, TPGDA, or PA.